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AERO-OPTICS AT SHORTER WAVELENGTHS

by

Allen E. Fuhs
Distinguished Professor

March 1980

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ABSTRACT

Using the optical system equation, the impact of a change in wavelength is determined. The rms phase variation at output aperture is critical and must be reduced by an amount equivalent to reduction in wavelength. If turret size is scaled with wavelength, the distortion due to the inviscid flow remains constant. Decreased wavelength offers the flexibility of greatly reduced turret weight, volume, and aerodynamic drag. Multiple turrets become feasible on an aircraft. The distortion due to the turbulent boundary layer becomes magnified by reduction of wavelength; however, if the turbulent boundary layer originates on the turret and if the turret is scaled, the boundary layer thickness decreases. Distortion becomes less significant in this case.

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AERO-OPTICS AT SHORTER WAVELENGTHS

by

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I. INTRODUCTION

An extensive technological base for aero-optics has been developed by the laser community. The research and development work was oriented to the CO₂ laser with wavelength of 10.6 microns. In recent times, lasers operating at much shorter wavelengths, e.g., iodine laser at 1.315 microns [1] or the excimer lasers in the blue end of the visible spectrum [2], have shown potential for superior performance. The information concerning laser turrets on aircraft needs to be reexamined for shorter wavelengths.

Section II discusses the far-field intensity using an equation which was developed by Holmes and Avizonis [3]. The equation highlights the impact of a change in wavelength. Section III discusses scaling of turret weight, volume, and drag. Section IV discusses the scaling of phase distortion due to inviscid flow. Section V considers phase distortion to aircraft generated turbulence. Finally Section VI summarizes the paper and states conclusions relative to unknowns or areas of uncertainty.

II. FAR-FIELD INTENSITY

An equation for far-field intensity has been developed by Holmes and Avizonis [3]. The equation, which is useful for systems analysis, is

$$I_{ff} = \left(\frac{\pi D^2 P}{4 \lambda^2 Z^2} \right) \frac{R^m_T T_d T_a K \exp[-(2\pi \delta_{rms}/\lambda)^2]}{\left(\frac{D}{FD_0} \right)^2 \left[1 + \left(\frac{5\sigma D}{3\lambda} \right)^2 \right]} \quad (1)$$

One additional term, D/FD_0 , has been added by Fuhs [4] to account for turbulence. The meaning of each term will be discussed now.

The first term is the far-field intensity on axis for an Airy diffraction pattern. The mirror diameter is D ; the laser power at the output aperture, i.e., laser telescope primary mirror, is P ; the wavelength of the laser is λ ; and the range to the focal plane is Z . The shorter wavelength increases I_{ff} ; however, one may want to decrease mirror size, thereby decreasing turret weight and volume. Further, a decrease in mirror diameter, D , will decrease aerodynamic drag. Consequently, the ratio of D to λ will be assumed to be constant, i.e.,

$$S_1 = \lambda/D = \text{constant} \quad (2)$$

S_1 is a scaling factor. The turret will have a characteristic dimension L . An additional assumption is

$$S_2 = L/D = \text{constant} \quad (3)$$

where S_2 is another scaling parameter.

The term for jitter is

$$1 + \left(\frac{5\sigma D}{3\lambda} \right)^2 = 1 + \left(\frac{5\sigma}{3S_1} \right)^2 \quad (4)$$

When S_1 is constant, the jitter term depends on the line-of-sight rms angular beam jitter, σ . Many different phenomena influence the magnitude of σ including the following:

aerodynamic inputs to airframe

aerodynamic input directly to the laser turret

aerodynamic input due to control surface deflections

unsteady aerodynamics in vicinity of laser turret

unsteady aerodynamics due to open port

vibration due to aircraft components

electrical noise within servo system

laser turret mechanical jitter

interaction of turret aerodynamics with remainder of aircraft

Each item will not be discussed. When the laser turret shrinks in size to maintain S_1 constant, the value of σ must be maintained constant to avoid increased detrimental effects.

From the causes of jitter listed above, the problem due to open port may be eliminated or decreased. With another wavelength, i.e., 1.3 microns instead of 10.6 microns, and a much smaller size, a window may become feasible.

The quantity R^m is the loss due to the reflectivity of m -mirrors in the optical train. T_w is the transmission of the window mentioned in the preceding paragraph. The quantity T_d is diffractive spillage around mirrors in the optical train. T_d is a function of Fresnel number

$$N_F = \frac{r_m^2}{\lambda \ell} = \frac{D_m^2}{4\lambda \ell} = \frac{D_m}{4S_1 \ell} \quad (5)$$

where r_m is the radius of mirrors in the optical train, and ℓ is the spacing between two mirrors. If one scales the primary mirror by ratio S_1 , then the diameter of a mirror in the optical train, D_m , undoubtedly will be scaled to a smaller size. The consequence is increased spillage, i.e., a smaller value for T_d . One assumes that ℓ remains fixed.

The transmission of the atmosphere is T_a and is given by

$$T_a = e^{-\gamma Z} \quad (6)$$

where γ is an extinction coefficient. The extinction coefficient is the sum of four terms

$$\gamma = \alpha_a + \alpha_s + k_a + k_s \quad (7)$$

where α_a is molecular absorption, α_s is molecular scattering, k_a is aerosol absorption, and k_s is aerosol scattering. Each of the terms in equation (7) is dependent on wavelength.

The factor K is a consequence of nonuniform intensity, I , watts/cm², at the primary mirror of the laser turret. If S_1 is fixed, the intensity in the far-field does not change; see Appendix A.

Aero-optics plays an important role in the factor $\delta_{\text{rms}}/\lambda$. Of course, δ_{rms} is the result of all optical aberrations starting within the cavity of the laser device. The aerodynamic window, the mirrors in the optical train, and the primary telescope mirror affect δ_{rms} . The beam propagates through a turbulent boundary layer and the variable density field generated by the inviscid flow over the turret. Both external flows contribute to δ_{rms} .

Obviously, when λ is decreased, δ_{rms} must be decreased by a like amount. Otherwise, I_{ff} is reduced. When λ is reduced from 10.6 microns to 1.3 microns, i.e., by a factor of 8, δ_{rms} must be reduced also by a factor of 8. The most difficult aspect of scaling to shorter wavelengths will be to reduce δ_{rms} .

A connection exists between $\psi(\xi, \eta)$ in equation (A-1) and $\delta_{\text{rms}}/\lambda$ in equation (1). For more details concerning the relationship between ψ and δ_{rms} , see Born and Wolfe [5].

A term, D/FD_0 , appears in equation (1) to account for turbulence. The term is adequate for systems analysis but is not appropriate for a detailed examination of aero-optics. The question of turbulent flow is deferred to Section IV.

III. SCALING TURRET WEIGHT, VOLUME, AND DRAG

Turret weight, W, can be scaled using the equation

$$\frac{W_2}{W_1} = \left[\frac{D_2}{D_1}\right]^n \tag{8}$$

where n is a number depending on the turret optics and D is output aperture.

Table I gives the value of n, W₁, and D₁ for three turrets.

Table I. Parameters for Turret Weight

Type of Turret	n	W ₁ , pounds	D ₁ , cm
on-gimbal Cassegrain	2.50	1637	60
heliostat	1.93	1788	60
coelostat	2.40	2161	60

Changing from a CO₂ laser to an iodine laser gives a wavelength ratio of 1/8. Assuming S₁ is fixed, the value of D can be reduced by a factor of 1/8; mirror diameter can be reduced from 60 cm to 7.5 cm. Use the numbers in equation (8) for an on-gimbal Cassegrain telescope. The result is

$$W_2 = 1637 \left[\frac{1}{8}\right]^{2.5} = 9.04$$

The range of validity of the scaling law of equation (8) may have been exceeded; even so, the qualitative conclusion is that turret weight is very significantly reduced.

Turret volume, V, follows a scaling law of

$$\frac{V_2}{V_1} = \left(\frac{D_2}{D_1}\right)^3 \tag{9}$$

Once again, significant reductions occur.

Aerodynamic forces are given by an equation of the form

$$F = \frac{1}{2}\rho u^2 AC_F \quad (10)$$

where C_F is a force coefficient. The drag is

$$D = \frac{1}{2}\rho u^2 AC_D \quad (11)$$

where C_D is the drag coefficient. In equation (11), A is the cross sectional area of the turret exposed to the flow. Hence the drag varies as mirror diameter squared.

When laser turrets weigh in tons, only one turret can be used on an aircraft. However, when the turret is reduced in weight and volume by a factor of 100 or so, many turrets can be used. Instead of attempting to cover 2π -steradians with one turret, each of the small turrets can cover a much smaller solid angle. Furthermore, the turrets can be located at many different places on the aircraft. In the enthusiasm to add turrets, consideration must be given to fire control, pointing, and tracking.

IV. SCALING OPTICAL DISTORTION DUE TO INVISCID FLOW

Three lengths are of relevance to the scaling of optical distortion due to inviscid flow; these are beam diameter, D ; wavelength, λ ; and characteristic turret dimension, L . One length is selected as a reference length to form ratios. Equations (2) and (3) indicate D is used as the reference.

Compressible flow over a laser turret generates a spatially varying density field. A relation exists between refractive index and density

$$n = 1 + (\kappa\rho/\rho_0) \quad (12)$$

The fractional changes are

$$\frac{\Delta n}{n} = \kappa \frac{\Delta\rho}{\rho} \quad (13)$$

By solving the equations of motion for flow over a turret, the density field can be obtained. Knowing the density field, the refractive index can be calculated.

The optical path length, OPL, is defined as

$$\text{OPL} = \int n(x,y,z)ds \quad (14)$$

where s is distance along a ray. The optical path length is a geometrical length weighted by the local refractive index. The change in OPL, known as optical path difference, OPD, is

$$\delta = \text{OPD} = \int n_i(x,y,z)ds_i - \int n_r(x,y,z)ds_r \quad (15)$$

where subscripts i and r indicate the i -th ray and a reference ray. The quantity δ is equal to the optical path difference.

Define nondimensional variables

$$x = x'D$$

$$y = y'D$$

$$z = z'D$$

$$s = s'D$$

Substitution of the nondimensional variables into equation (14) gives

$$\text{OPL} = D \int n(x',y',z')ds' \quad (16)$$

Likewise the optical path difference becomes

$$\delta = D \int n_i ds'_i - D \int n_r ds'_r \quad (17)$$

Hence OPL and δ scale as mirror diameter D . One must show that the integrals in equations (16) and (17) are constant when turret size varies so that S_1 and S_2 are constant.

For blunt turrets, the equation for the velocity potential in compressible flow is

$$\frac{1}{a^2} \frac{\partial \phi}{\partial x_i} \frac{\partial \phi}{\partial x_k} \frac{\partial^2 \phi}{\partial x_i \partial x_k} = \frac{\partial^2 \phi}{\partial x_j \partial x_j} \quad (18)$$

Introduce nondimensional variables

$$\phi = \phi' u_\infty D$$

$$u = u' u_\infty$$

$$a = a' a_\infty$$

into equation (14). The result is

$$\frac{M_\infty^2}{a'^2} \frac{\partial \phi'}{\partial x'_i} \frac{\partial \phi'}{\partial x'_k} \frac{\partial^2 \phi'}{\partial x'_i \partial x'_k} = \frac{\partial^2 \phi'}{\partial x'_j \partial x'_j} \quad (19)$$

A length scale parameter does not appear in equation (19). Although not demonstrated here, the boundary conditions can be nondimensionalized without a residual length scale. Consequently, the solution ϕ' is independent of turret scale.

The local Mach number is related to freestream Mach number by

$$M = \frac{u}{a} = \frac{u' u_\infty}{a' a_\infty} = M_\infty M' \quad (20)$$

The local Mach number determines the local refractive index. Since M' is independent of turret scale, the identical value of refractive index exists at corresponding points in two flows with different scale. Consequently, the integrals in equations (16) and (17) are identical for the two flows at different scale.

The phase distortion, also known as optical path difference, relative to wavelength is

$$\frac{\delta}{\lambda} = \frac{D}{\lambda} \int n_i ds'_i - \frac{D}{\lambda} \int n_r ds'_r \quad (21)$$

Since the integrals are independent of scale, and since S_1 is fixed, the phase distortion does not vary. Likewise $\delta_{\text{rms}}/\lambda$ does not vary with turret scale provided M_∞ , S_1 , and S_2 are fixed.

For small perturbation turrets, a similar argument can be made.

V. VISCOUS FLOW PHENOMENA LEADING TO OPTICAL DISTORTION

A. Types of Viscous Flow Phenomena

Viscosity dominates and determines, at least in part, the gross characteristics of several different types of flow. These include boundary layers, shear layers, open port cavities, wakes, and shock waves. Although not a flow of the same nature as those listed above, jet engine exhausts should be included; exhausts can have a detrimental effect on beam propagation. At the speeds and geometric scales involved with aircraft, the viscous flows lead to turbulence. Extensive literature [6-21] exists on the propagation of electromagnetic waves through a turbulent medium.

Boundary layers surround the aircraft surfaces. The boundary layer on leading edges and forward surfaces is laminar with transition occurring at a critical Reynolds number. Flow separation leads to shear layers. Shear layers separate two flow regions with different flow velocities.

Due to the extremely high irradiance in the laser beam, the turret may have an open port. Windows are not available which can survive the high irradiance. The interior of the turret is a cavity in which unsteady, turbulent flow exists. The flow in a cavity may have regularity in the sense that discrete vortices can be identified.

Wakes are turbulent and adversely affect propagation. When selecting a location for a laser turret, any location within or near a wake should be avoided.

Shock waves create large changes in density and refractive index. Shock waves which originate or reflect from boundary layers create intense turbulence. Depending on conditions, a triple point may occur in reflection of an oblique shock. Downstream of the triple point, a shear layer exists. Also downstream of a reflected shock, a separated flow region may occur.

Two cases can be identified. In one case, the laser beam propagates through a region disturbed by a shock wave. In the other case, the shock wave originates or reflects near the aperture of the turret. The latter case causes the greater difficulty with optical distortion.

B. Turbulent Boundary Layers

The boundary layer may originate on aircraft surfaces far upstream of the aperture. If this is the case, then the boundary layer will be thick. When the laser turret protrudes into the flow, the boundary layer may begin on the turret itself. In that case, the boundary layer is thin. One can state unequivocally that the thinner the boundary layer, the lesser the adverse influence on beam quality.

In addition to the distance which the boundary layer has traversed, other factors influence the boundary layer. Mach number characterizes the compressibility effects. At higher Mach numbers, the boundary layer tends to grow in thickness. Wall curvature, which usually is accompanied by pressure gradients, has an influence on boundary layer thickness and velocity profile. When the wall is concave to the external flow, Gortler vortices may occur. Cooling or heating can alter boundary layer properties. In fact, cooling may be one approach to flow control. Surface roughness may amplify turbulent intensities. Surface roughness may be due to rivet heads, structural joints, insects which have smeared the surface, etc.

Pressure gradients have been mentioned earlier. A gradient in which the pressure increases in the flow direction is termed an adverse gradient. Conversely, a gradient with decreasing pressure in the flow direction is a favorable gradient. Adverse pressure gradients lead to flow separation as well as thicker boundary layers. Favorable pressure gradients delay transition from laminar to turbulent flow. Favorable pressure gradients tend to cause thinner boundary layers. A boundary layer in a favorable pressure gradient rarely separates.

Shock wave, boundary layer interaction has been mentioned. If the interaction occurs at the aperture or immediately upstream of the aperture, severe beam degradation is likely.

For turbulent incompressible boundary layers, the thickness, δ , is given by [22]

$$\frac{\delta}{x} = 0.37 \text{ Re}_x^{-0.2} \quad (22)$$

According to equation (22), δ increases as x to + 0.8 power. For a laminar, compressible boundary layer, the thickness is given by [23]

$$\delta = C_1 \text{Re}_x^{0.5} \left[1 + C_2 \frac{\gamma - 1}{2} M^2 \right] \quad (23)$$

where C_1 and C_2 are constants. Turbulent compressible boundary layers show similar trends with increasing Mach number.

A boundary layer in compressible flow has a temperature gradient across the boundary layer. The gradient in temperature is due to viscous dissipation. A quantity known as the recovery factor r is defined for an adiabatic wall; r is

$$r = \frac{T_w - T_\infty}{T_0 - T_\infty} = \text{Pr} \quad (24)$$

The temperature of the wall is T_w , the temperature of the air at the outer edge of the boundary layer is T_∞ , and the stagnation temperature is T_0 . Equation (24) shows r equal to the Prandtl number, Pr . An effective Prandtl number can be defined for a turbulent boundary layer and will have a value near unity. Hence the wall temperature will be equal to the stagnation temperature when $Pr = 1.0$.

The rms density fluctuations in the turbulent boundary layer are related to the difference in density at the wall, ρ_w , and at the edge of the boundary layer, ρ_∞ . According to Sutton [24]

$$\rho_{rms} \approx 0.1(\rho_\infty - \rho_w) \quad (25)$$

for boundary layers with supersonic external flow. For subsonic boundary layers, the constant is larger than 0.1 shown in equation (25). The density at the wall is given by

$$\rho_w = \frac{P_\infty}{RT_w} \quad (26)$$

The rms fluctuation in refractive index is related to density by

$$\frac{n_{rms}}{n} = \kappa \frac{\rho_{rms}}{\rho} \quad (27)$$

where κ is the constant from equation (12).

An attenuation coefficient, α , can be defined for propagation through a layer of a turbulent medium. The intensity ratio is

$$\frac{I}{I_0} = e^{-\alpha\delta} \quad (28)$$

where the layer thickness is δ , and I_0 is the intensity of the beam entering the layer. The attenuation is due to scattering by the turbulent boundary layer. Sutton [25] gives a formula for α as follows:

$$\alpha = 2k^2 n_{\text{rms}}^2 \Lambda \quad (29)$$

where k is the wavenumber equal to $2\pi/\lambda$ and Λ is the macroscale of the turbulence. The macroscale is obtained from

$$\Lambda = \int_0^{\infty} C(r) dr \quad (30)$$

where $C(r)$ is the correlation function for refractive index in an isotropic turbulent medium. The correlation function is given by

$$C(r) = \frac{\int_0^{\infty} \Delta n(r+R) \Delta n(r) 4\pi R^2 dR}{\int_0^{\infty} [\Delta n(R)]^2 4\pi R^2 dR} \quad (31)$$

where Δn is the deviation from the average, \bar{n} ,

$$\Delta n = n(r) - \bar{n} \quad (32)$$

Sutton [25] reports values of the scale of turbulence equal to about 0.1δ , i.e., the scale of turbulence is approximately 1/10 of the boundary layer thickness.

For propagation through turbulent boundary layers, several characteristic lengths occur as follows:

Λ	macroscale of turbulence
δ	boundary layer thickness
D	aperture for laser beam
λ	wavelength of laser radiation

Many regions for turbulent propagation can be characterized by the length scales along with the extinction number $\alpha\delta$.

C. Scaling Propagation Through a Turbulent Boundary Layer of Fixed Thickness

Two parameters can be used to characterize the degradation in beam quality due to turbulence. One is the decrease of intensity, watts/cm^2 , on the axis of the beam in the far-field. For large values of D/Λ , equation (28) provides a means to calculate I/I_0 . The second parameter is the half-intensity angle for the beam. The half-intensity angle, $\theta_{1/2}$, defines a cone with a vertex angle equal to $\theta_{1/2}$. On the surface of the cone, the intensity is one-half of the peak intensity.

Figure 1 shows the half-intensity angle as a function of the ratio D/Λ . The ordinate is the variable $\theta_{1/2}/(1.129\lambda/D)$. This variable compares the half-intensity angle for the scattered beam with the half-intensity angle for a diffraction limited beam.

Consider a CO_2 laser beam at 10.6 microns from a $D = 60$ cm mirror. Assume the boundary layer thickness, δ , is 10 cm, and the macroscale, Λ , is 1 cm. For $M = 1.5$ flow with turbulent Prandtl number of unity and $p_\infty = 1$ atmosphere, $\rho_\infty = 1.23 \text{ kg/m}^3$, and $T_\infty = 290^\circ\text{K}$, the values of ρ_w and ρ_{rms} are 0.848 kg/m^3 and 0.038 kg/m^3 . Using $\kappa = 2.4 \times 10^{-4}$, the value of n_{rms}/n is 7.44×10^{-6} . The extinction coefficient, which is calculated using equation (29), is 0.39 per meter. The extinction number, $\alpha\delta$, is 0.039, and D/Λ is 60. The corresponding point can be plotted in Figure 1, giving $\theta_{1/2}/(1.129\lambda/D)$ almost on the dotted line.

Consider now an iodine laser at 1.315 microns with a turret for which $D/\lambda = S_1$ has been maintained constant. Hence $D = 7.44$ cm; also, D/Λ is 7.44. The extinction coefficient grows to

$$\alpha = (0.39)(8.06)^2 = 25.34$$

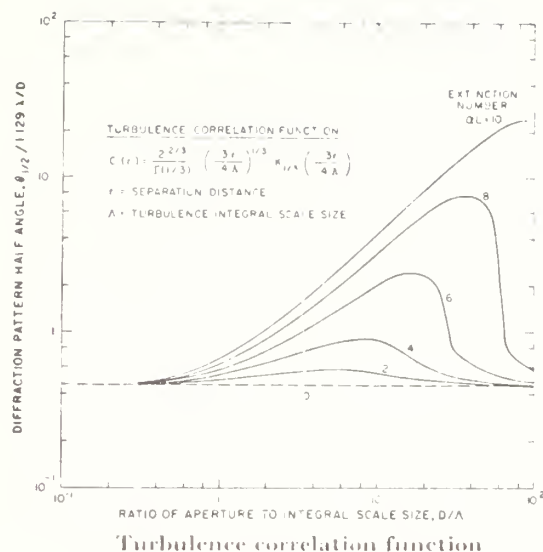


Figure 1. Diffraction angle for which the intensity is one half the maximum value. Reproduced from Sutton [25].

and the extinction number is 2.53. The point for the iodine laser can be plotted in Figure 1, giving a half angle parameter of about 0.6. The increase in half angle is about 20 per cent.

For a thicker turbulent boundary layer with $\delta = 20$ cm, the results are more dramatic as shown in Table II. The half angle parameter increases from 0.48 to 1.2, which is a factor of 2.5.

It should be emphasized that equation (28) does not apply when D/Λ is less than approximately 10. The attenuation is less than that predicted by equation (28) when $D/\Lambda < 10$.

D. Scaling Propagation Through a Scaled Turbulent Boundary Layer

This subsection discusses the case for which the turbulent boundary layer originates on the laser turret instead of an aircraft surface. From equation (22), the ratio of boundary layer thicknesses is

Table II. Change of Half Angle with Change in Wavelength

wavelength, λ , micron	10.6	1.31
boundary layer thickness, δ , cm	20	20
macroscale, Λ , cm	2	2
extinction coefficient, α , per meter	0.78	50.67
extinction number, $\alpha\delta$	0.156	10.13
ratio D/Λ	30	3.72
ratio D/λ	56,603	56,603
Mach number M	1.5	1.5
pressure, p_∞ , atmosphere	1	1
density, ρ_∞ , kg/m ³	1.23	1.23
temperature, T_∞ , °K	290	290

$$\frac{\delta_2}{\delta_1} = \left(\frac{x_2}{x_1}\right)^{0.8} = \left(\frac{L_2}{L_1}\right)^{0.8} \quad (33)$$

Further, the ratio of macroscales of turbulence is

$$\frac{\Lambda_1}{\Lambda_2} = \frac{\delta_2}{\delta_1} \quad (34)$$

The extinction number scales as

$$\frac{\alpha\delta)_2}{\alpha\delta)_1} = \frac{\lambda_1^2}{\lambda_2^2} \frac{\Lambda_2}{\Lambda_1} = \frac{L_1^2}{L_2^2} \left(\frac{L_2}{L_1}\right)^{0.8} = \left(\frac{L_1}{L_2}\right)^{1.2} \quad (35)$$

Equation (35) assumes n_{rms} is not changed. The ratio D/Λ scales as

$$\frac{D/\Lambda_2}{D/\Lambda_1} = \frac{L_2}{L_1} \frac{\Lambda_1}{\Lambda_2} = \frac{L_2}{L_1} \left(\frac{L_1}{L_2}\right)^{0.8} = \left(\frac{L_2}{L_1}\right)^{0.2} \quad (36)$$

Using equations (35) and (36) along with data of Table II, the following values are found for $\lambda = 1.315$ microns:

$$D/\Lambda = 19.8$$

$$\alpha\delta = 1.89$$

Plotting the preceding points in Figure 1 yields a $\theta_{1/2}$ about 8 per cent larger. The impact of reduced λ is much less when the boundary layer originates on the turret.

VI. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The analysis has assumed that $S_1 = \lambda/D$ and $S_2 = L/D$ were maintained constant as λ was decreased. The conclusions are valid for this case.

Using the optical system equation of Holmes and Avizonis [3], various consequences of reducing λ were examined. In summary, the following should be noted:

- δ_{rms} Phase distortion must be reduced by a factor of 8 for a change from CO_2 to iodine laser.
- K A factor which depends on the spatial distribution of intensity at the output aperture will not vary.
- T_d Diffractive spillage will tend to increase reducing the value of T_d .
- σ rms jitter can be maintained constant without change in I_{ff} .

Detailed comments were not made about atmospheric extinction coefficient; however, scattering tends to increase as λ decreases.

Turret weight and volume as well as turret aerodynamic drag will be reduced dramatically. Much greater flexibility in the number and location of turrets is a consequence. Further, the possibility of obtaining a suitable window should improve; open port problems are thereby circumvented.

The analysis shows that the phase distortion δ/λ for inviscid flow is given by

$$\frac{\delta}{\lambda} = (\text{constant}) \frac{D}{\lambda} \quad (37)$$

Since D/λ is constant, the phase distortion due to inviscid flow is independent of wavelength. The statement is true provided S_1 and S_2 are fixed. Nonetheless severe degradation due to the inviscid flow field can occur; hence, the problem cannot be ignored.

For turbulent boundary layers, the value of the extinction number, $\alpha\delta$, increases as λ decreases. Also, the ratio D/λ decreases as λ decreases. Since extinction and scattering depend on $\alpha\delta$ and D/λ , the trends are not favorable. The half-intensity angle increases, and extinction increases as λ decreases. Turbulent boundary layers require more attention.

Any change which causes a thinner turbulent boundary layer tends to improve beam quality. Mounting the laser turret at points farther forward decreases δ . Cooling the wall in the supersonic case also should be an improvement. Finally, attention to surface roughness should help reduce scattering and attenuation.

When the turbulent boundary layer originates on the laser turret, the boundary layer thickness decreases as the turret decreases in size. Hence, the impact of the turbulent boundary layer on $\theta_{1/2}$ is almost unchanged by a change in λ ; however, serious degradation in intensity due to $\alpha\delta$ remains.

APPENDIX A

Consider the change in intensity at some point P in the far-field of an aperture illuminated in phase and amplitude by

$$F(\xi, \eta) = A(\xi, \eta) e^{j\psi(\xi, \eta)} \quad (\text{A-1})$$

Silver [26] on page 173 shows the amplitude and phase of the wave at point P is given by

$$U_P = \frac{j}{\lambda R} e^{-jkR} \int_A F(\xi, \eta) \exp[jk \sin \theta (\xi \sin \phi + \eta \cos \phi)] d\xi d\eta \quad (\text{A-2})$$

Intensity at point P is

$$I_P = U_P U_P^* \quad (\text{A-3})$$

Introduce nondimensional variables

$$\xi = \xi' D \quad \eta = \eta' D \quad (\text{A-4})$$

where D is the diameter of the aperture. The integration in equation (A-2) extends over $A = \pi D^2/4$. Examine first the exponent in the integrand of equation (A-2); it becomes

$$jk \sin \theta [\xi \sin \phi + \eta \cos \phi] = jkD \sin \theta [\xi' \sin \phi + \eta' \cos \phi] \quad (\text{A-5})$$

Note that

$$kD = 2\pi/S_1 \quad (\text{A-6})$$

The complex function $F(\xi, \eta)$ is exactly the same as equation (A-1) except primes are added to ξ and η . The integral in equation (A-2), which is represented by I_n , becomes

$$D^2 I_n = D^2 \int_{A'} F(\xi', \eta') \exp[j(2\pi/S_1) \sin \theta (\xi' \sin \phi + \eta' \cos \phi)] d\xi' d\eta' \quad (\text{A-7})$$

The intensity at point P is obtained by combining equations (A-2), (A-3), and (A-7)

$$I_P = \frac{D^2 I_n^2}{\lambda^2 R^2} = \frac{I_n^2}{S_1^2 R^2} \quad (A-8)$$

Consider two cases 1 and 2 which differ in the wavelength of radiation but for which S_1 is constant. The ratio of intensities becomes

$$\frac{I_{P2}}{I_{P1}} = \frac{I_{n2}^2}{I_{n1}^2} \frac{R_1^2}{R_2^2} \quad (A-9)$$

In equation (A-9), the integrals, I_n , cancel when P is located at the same point specified by R, θ, ϕ . Since $R_1 = R_2$, the ratio of intensities is identical. Consequently, the factor K in equation (1) is identical for cases 1 and 2.

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